**Development of Algorithms and Strategies for Monitoring Chlorophyll
and Primary Productivity in Coastal Ocean, Estuarine and
Inland Water Ecosystems**

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**Summary**

This is the semi-annual technical report for the period January through July 2001 for the Execution Phase of my MODIS Instrument Team investigator project.  The objectives of this work are:

- Establish a protocol for developing regional or site-specific bio-optical algorithms for coastal "case 2" waters.
- Prescribe a protocol for "stitching together" local or site-specific algorithms.
- Demonstrate these protocols in two coastal seas:  the Gulf of Maine/Mid-Atlantic region, and the Yellow Sea/East China Sea region.
- Develop a strategy for monitoring coastal oceans, estuaries, and inland waters.

This report reflects the efforts of a research team consisting of myself, three staff scientists (Dr. Mark Dowell, Timothy Moore, and Ken Jacobs), and two Ph.D. students (Hui Feng and Seung-Hyun Son).

Papers published or submitted:

1. Joe Salisbury, Janet Campbell, David Meeker, and Charles Vorosmarty, "Ocean Color and River Data Reveal Fluvial Influence in Coastal Waters"  EOS Transactions, American Geophysical Union, **82**(20), May 15, 2001.

2. Moore, T. S., J. W. Campbell and H. Feng.  "A fuzzy logic classification scheme for selecting and blending satellite ocean color algorithms" *IEEE Trans. in Geosciences and Remote Sensing*, in press, July, 2001.

3. Janet Campbell, David Antoine, Robert Armstrong, Kevin Arrigo, William Balch, Richard Barber, Michael Behrenfeld, Robert Bidigare, James Bishop, Mary-Elena Carr, Wayne Esaias, Paul Falkowski, Nicolas Hoepffner, Richard Iverson, Dale Kiefer, Steven Lohrenz, John Marra, Andre Morel, John Ryan, Vladimir Vedernikov, Kirk Waters, Charles Yentsch, and James Yoder "Comparison of algorithms for estimating ocean primary productivity from surface chlorophyll, temperature, and irradiance."  (submitted to Global Biogeochemical Cycles, June 2000; reviewer comments received April 2001 (!), revised manuscript returned, May 2001, current status unknown).

Presentations (Jan-July 2001):

4.  Mark Dowell, Janet Campbell, and Timothy Moore. "A Strategy to Merge MODIS Level 4 Ocean Primary Production Products" poster presented at the MODIS Science Team Meeting, Columbia, MD, January 2001

5.  Janet Campbell, Timothy Moore, and Mark Dowell, "A Strategy to Blend MODIS Ocean Products for Case 1 and Case 2 Waters" poster presented at the MODIS Science Team Meeting, Columbia, MD, January 2001

6.  Janet Campbell, "A fuzzy logic scheme for selecting and blending ocean color algorithms" Presented at the SIMBIOS Science Team meeting, Jan. 30, 2001.

7.  Janet Campbell, "Ocean Color Remote Sensing: New frontiers in algorithms and applications" Seminars given at UMass-Dartmouth and UMass-Boston, Feb. 2001.

8.  Janet Campbell, Mark Dowell, and Timothy Moore, "Dynamic Ocean Provinces: Fuzzy logic applied to global satellite data." Presented at the NASA Oceanography Symposium, Miami, April 2001.

9.  Janet Campbell, "The Potential Application of MODIS to Coastal Monitoring" Invited presentation, EMAP Symposium 2001: Coastal Monitoring through Partnerships, April 2001.

10. Janet Campbell, Timothy Moore, and Seung-Hyun Son, "Toward the Creation of a Multi-decadal Time Series of Global Ocean Chlorophyll Concentration" presented at the NASA Ocean Color Science Team Meeting, San Diego, May 2001.

11. Timothy Moore, Mark Dowell, and Janet Campbell, "Dynamic Bio-Optical Provinces as Defined by Fuzzy Logic Applied to Satellite Radiance Data." presented at the NASA Ocean Color Science Team Meeting, San Diego, May 2001. (Manuscript now in draft form).

12. Mark Dowell, Timothy Moore, and Janet Campbell, "Dynamic Ecological Provinces: An Objective Bio-geography for Modeling Ocean Primary Production." presented at the NASA Ocean Color Science Team Meeting, San Diego, May 2001. (Manuscript now in preparation).

13. Charles Vorosmarty, Janet Campbell, Pamela Green, Joe Salisbury "Global Hydrological Archive and Analysis System and its Application to Coastal Studies, presented at the NASA Ocean Color Science Team Meeting, San Diego, May 2001.

14. Janet Campbell, "Ocean Color and Primary Productivity" Presentation at the NASA Goddard Graduate Student Seminar Series on The Global Carbon Cycle: The Role of Carbon in the Earth's Climate, Greenbelt, MD, June 2001.

15. Janet Campbell, "Satellite-based estimation of marine primary production: current status and future directions" presented at the JGOFS Global Synthesis Task Team Meeting, Amsterdam, July 2001.

16. Mark Dowell, Timothy Moore, and Janet Campbell "Dynamic Ecological Provinces: An Objective Bio-Geography Based on Global Satellite Data" IGBP meeting "Challeges of a Changing Earth" Amsterdam NL, 10-13 July, 2001.

**Case 2 Algorithm Protocol Development**

There are two areas of algorithm development that are addressed in this project. One is the bio-optical algorithm which retrieves chlorophyll and other optically-active constituent concentrations. The second area is the primary productivity algorithm.

Bio-optical algorithms

The strategy for this work has been to promote the use of a standard semi-analytic remote-sensing reflectance model that relates remote-sensing reflectance to inherent optical properties (absorption and backscattering coefficients), and then to prescribe methods for parameterizing the IOPs as functions of the constituent concentrations of interest (chlorophyll, colored dissolved organic matter, and suspended sediment). We also advocate the need for regional- or class-specific models to accommodate the wide range of bio-optical variability found in natural waters. A method has been developed (paper # 2) to select and blend bio-optical algorithms for ocean color thus allowing smooth transitions across ocean water boundaries (e.g., Case I to Case II). Recently we have extended this approach to the global scale where a finite number of distinct optical classes are identified and considered adequate to describe the global variability in optical properties. A cluster analysis based on the fuzzy $c$-means (FCM) method was performed on a global in-situ data set of over 1,700 reflectance measurements in which 6 distinct optical classes were identified. Of these 6 classes, 4 are oceanic and exhibit optical properties consistent with Case I waters. The two remaining classes may be broadly considered coastal/Case II waters, each of which has distinct optical characteristics and active constituents. This work has been presented in several venues (most recently, presentations 10 and 11), and there are two companion papers currently being prepared based on these presentations.

When applied to satellite data, the core of the method is the fuzzy membership function which assigns class memberships to all pixels in a satellite image. This function uses class-specific reflectance statistics derived from in-situ data to calculate a membership value ranging from 0 to 1 for each pre-defined class, allowing each pixel to have partial membership to one or more classes. When applied to SeaWiFS global composite images, class membership maps reveal coherent regional and global-scale patterns which represent optically-distinct ocean provinces. These class membership values can be used to weight and blend class-specific algorithm retrievals (i.e., chlorophyll a, CDOM absorption, and particle backscattering).

<u>Primary productivity algorithms</u>

Work in this area is progressing on several fronts:

1.  We are working on an algorithm for computing primary production in coastal waters based on a wavelength-resolved model of photosythetically usable radiation (PUR). This was described in detail in our January 2001 progress report. The manuscript is still in preparation.

2.  We have made considerable progress toward the application of the fuzzy logic scheme to define provinces for primary production estimation. This approach uses as input satellite-derived fields of chlorophyll, SST, and PAR. We have identified 9 distinct classes or ecological provinces using the primary productivity data base of Behrenfeld and Falkowski (http://marine.rutgers.edu/opp) augmented with primary productivity measurements at 85 coastal stations. Our goal is to determine a model of $\psi^*$ for each province. Thus when a satellite image is processed, the fuzzy memberships can be calculated and results blended to yield a global PP map. To merge this and the other two existing MODIS primary production products into a single global PP map, the application of fuzzy logic techniques will be taken one step further. We have evaluated the performance of each of the current MODIS primary productivity algorithms in the 9 different provinces. At present, we are limited in available PP data sets for validation, since this should involve an independent data set not used in any of the algorithm development processes.

3.  A  graduate student (Seung-Hyun Son) is working on primary productivity algorithms for the Yellow Sea.

**Protocol for "Stitching Together" Algorithms**

The manuscript (#1) submitted to the *IEEE Transactions on Geoscience and Remote Sensing* is now in press. It describes this protocol.

How does this relate to MODIS data?  At the present time, there are 3 MODIS chlorophyll products, and 3 pigment products.  One of the pigment products is the "coccolithophore pigment" which is only relevant in coccolithophore-dominated waters. Such waters might be regarded as one of the optical water classes and a fuzzy logic scheme could be implemented to distinguish these waters. More broadly, the fuzzy logic classification and membership scheme could be used to differentiate water types that would be most appropriate for applying the various MODIS algorithms. The table on the following page illustrates this concept.

Implementation of such a scheme under the present MODIS data processing environment would be unrealistic (if not impossible).  However, MODIS products can be blended using this approach after they are created.  Thus, either with the appropriate software (e.g., in SeaDAS) or by the DAAC, a blended product can be created using existing MODIS chlorophyll products.

| Water Class | Algorithm to Apply | Comments |
|---|---|---|
| Case 1: oligotrophic | Chlor_MODIS (MOD 19, parameter 14) | This is the standard MODIS Case 1 algorithm |
| Case 1: mesotrophic | Chlor_a_2 (MOD 21, parameter 26) | This 3-band algorithm is designed to be consistent with the SeaWiFS 4-band OC4.v4 algorithm currently used to derive the SeaWiFS Chlorophyll. It is the OC3M algorithm documented in NASA TM 2000-206892, Vol. 11. |
| Case 1: Eutrophic or Case 2: CDOM dominated with packaged cells | Chlor_a_3 (MOD 21, parameter 27) | This is the standard MODIS Case 2 algorithm, cells are large and contain "packaged" chlorophyll |
| Case 2: CDOM dominated with unpackaged cells | Chlor_a_3 (MOD 21, parameter 27) | This is the standard MODIS Case 2 algorithm: smaller cells generally found in low-nutrient environments |
| Coccolithophore dominated waters | Cocco_pigmt_conc (MOD 25, parameter 20) | This would be used if coccolithophores dominate the population. |

**Demonstration in Gulf of Maine and Yellow Sea Regions**

We are continuing to assemble a data base of in-situ bio-optical data for the two demonstration sites: Gulf of Maine and Yellow Sea. We have ordered MODIS data for these areas.

**Development of Monitoring Strategies**

The proposal submitted by the Hong Kong University of Science and Technology described in the January 2001 report was turned down.

No further progress has been made in this area. However, a presentation describing the potential of MODIS for coastal monitoring was presented at the EMAP Symposium (presentation # 9).

**Support of MODIS Ocean Team Activities**

Our activities for the past 6 months have focused on evaluating the various MODIS products and comparing them with SeaWiFS data acquired at the same location and on the same day. At the MODIS Oceans team meeting in Miami in April 2001, we presented a comparison of MODIS water-leaving radiances with SeaWiFS radiances, and the various MODIS chlorophyll products with each other and with SeaWiFS chlorophyll. We used a pair of scenes from May 8, 2001 in which MODIS and SeaWiFS data were acquired approximately one hour apart.

At that meeting, we recommended that the chlor_a_2 product be changed from the OC2 algorithm to one that is more consistent with the current SeaWiFS chlorophyll (OC4).

We then conducted an analysis in which we evaluated 3 candidate algorithms. We evaluated the algorithms first using an in-situ data set of 1,229 stations ranging from oligotrophic to coastal Case 2 waters, and second using nearly coincident MODIS and SeaWiFS images. We concluded this by recommending that the OC3M algorithm be used (see above Table, and NASA TM 2000-206892, Vol. 11). A powerpoint presentation detailing the results of this study was created and provided to Wayne Esaias.

I am currently writing an overview document which summaries the various MODIS chlorophyll products and refers (links) to the respective Quality Summaries. In addition, I am preparing a Quality Summary for the chlor_a_2 product which is now based on the OC3M algorithm.

**Challenges Associated with MODIS Data**

In our January 2001 progress report, we described challenges associated with acquiring and handling MODIS data. More recently, we responded to an inquiry from Skip Reber asking for comments on data processing and availability issues. We prepared a summary statement which was given to Skip Reber and Vince Salomonson.

**Progress in Related Areas**

My graduate student, Joe Salisbury, has recently published an article in the EOS Transactions (AGU newsletter) (paper #1 listed above). This is part of his dissertation research, which is aimed at linking coastal ocean color data to riverine discharge and water chemistry.

The preproposal submitted to the NOAA-UNH Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) described in the January 2001 report was not successful.

We are collaborating with Anthony Liu, Yunhe Zhao, and Wayne Esaias to evaluate the use of MODIS and SeaWiFS images made on the same day to derive mixed layer drift (horizontal advection). Anthony Liu and Yunhe Zhao have applied a wavelet algorithm to calculate motion vectors of the May 8, 2000 scene off the U.S. East Coast. The method looks promising, and will be even more powerful when the MODIS Aqua data are available, thus providing a third observation on the same day.